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DESIGN, FABRICATION AND TESTING OF A 4-WAY CATALYTIC CONVERTER FOR REDUCING EXHAUST EMISSION POLLUTION IN A DIESEL AUTOMOBILE ENGINE

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ABSTRACT

Demand for automobiles is increasing by the day all over the world. Diesel oil being cheaper than gasoline, diesel vehicles are being used for personal purposes than the commercial applications. It is projected that by 2030, 1300 million automobiles will be plying on roads. Due to incomplete combustion of fuel oil pollutants like CO, HC, and NOx are released into atmosphere causing negative impact on air quality, environment and human health.

Researchers all over the world concentrated on how to reduce the pollutants. Euro norms specify the allowable percentages of CO, HC and NOx in the exhaust gases. Euro norms being implemented in the developed countries have given stringent values, which has led to the development of catalytic converter which is added equipment in automobile. Hitherto in the catalytic converters supplied in modern cars, Platinum and Rhodium metals are used for coating monoliths. These metals are rare, and hence expensive. From Euro 4 onwards NO_x values are reduced drastically. Hence, NO_x abatement has become a major issue.

In the research carried out by authors, alternative coating materials like CeO_2, ZrO_2 which help NO_x abatement and oxygen storage are used over clay marbles. These were designed, fabricated and tested on automobiles. The results are encouraging showing marked fall of pollutants in exhaust gases.

***KEYWORDS:** Diesel Oil, Pollutants, Clay Marbles, Abatement & Oxygen*

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Original Article

INTRODUCTION

The use of catalytic converter came in to existence after 1975, before which an extensive research and studies were made in controlling the pollution emitted by the automobiles. The problem of pollution control was tackled in different levels from 1975 till date. Initially, efforts were made to improve fuel quality. Next step was to improve the engine design. As the Euro norms were stringent by every decade, from Euro I to VI, researchers concentrated on emission reduction using external equipment like a catalytic converter.

In the very early stage to control the pollution from the automobiles, a PCV (positive crank ventilation) system was designed, whose function is to collect the unburnt hydrocarbons and burn them, rather than to release into atmosphere. By the year 1984, most of the cars in US were equipped with PCV and became standard

equipment on all the vehicles.

Later on, to reduce the emitted pollution from the automobiles, tuning of the engines and use of leaded petrol has been made. In order to meet the standards set by the EPA, it became quite difficult for the tuning techniques as they were seriously reducing the engine efficiency, and thus leading to increase in fuel usage.

The recent norms to be used in the European Union is EURO VI, which is a frame work that dictates the limits of pollutants that different mobile sources can produce to be commercially available in the European union. The norm limits the production of total hydrocarbons (THC), Non-Methane hydrocarbons (NMHC), Nitrogen oxides (NOx) and Carbon monoxides (CO) and Particulate matter (PM). PM has been retained at 0.005 from Euro 5 onwards. But, NO_x values are drastically reduced from 0.5 in Euro 3 to 0.08 in Euro 6 for diesel engines.

Table 1: European Emission Standards

Tier	Date	CO g/km	THC g/km	NMHC g/km	NOx g/km	HC+NOx g/km	PM g/km
Diesel							
Euro 1	July 1992	2.72	-	-	-	0.97	0.14
Euro 2	January 1996	1.0	-	-	-	0.7	0.08
Euro 3	January 2000	0.64	-	-	0.5	0.56	0.05
Euro 4	January 2005	0.50	-	-	0.25	0.30	0.025
Euro 5	September 2009	0.50	-	-	0.18	0.23	0.005
Euro 6	September 2014	0.50	-	-	0.08	0.17	0.005
Gasoline							
Euro 1	July 1992	2.72	-	-	-	0.97	-
Euro 2	January 1996	2.2	-	-	-	0.5	-
Euro 3	January 2000	2.3	0.2	-	0.15	-	-
Euro 4	January 2005	1.0	0.1	-	0.08	-	-
Euro 5	September 2009	1.0	0.1	0.068	0.06	-	0.005
Euro 6	September 2014	1.0	0.1	0.068	0.06	-	0.005

India has adopted euro norms I and II in the year 2000. Presently, in the year 2010, euro III norms were implemented, and they are renamed as Bharat stage I, II, III, IV, V and VI (proposed through 2020). Bharat stage V stipulates a reduction of 28% NO_x and 93% PM values.

Table 2: Comparison of BS_4 and BS_5 Emission Norms for N_1 Class 3 Vehicle

Emission Norms	CO g/km	HC+NO_x g/km	NO_x g/km	PM g/km
Bharat Stage IV	0.74	0.46	0.39	0.06
Bharat Stage V	0.74	0.36	0.28	0.0045
% Less	NO change	22	28	93

The catalytic converter in an automobile is an expanded section of exhaust pipe occurring upstream of the muffler, in which pollutants generated in the engine are converted to normal atmospheric gases. It is an essential element in the emissions control system of modern automobiles. Early catalyst systems, as applied to vehicles with carburetors, attempted to oxidize carbon monoxide (CO) and unburned hydrocarbons (HC) to carbon dioxide (CO2) and water vapor, using air added by means of an air pump or rapidly actuating valve system.

There are mainly two types of devices that are used in decontamination of air based on the methods used for purification. They are Physical and Chemical. Catalytic converters utilize chemical reactions between the catalyst and the pollutant to remove the contamination. There are two types of catalytic reactions that take place in a catalytic converter:

reduction catalysts and oxidation catalysts, and they both work on the concept of transforming pollutants into less harmful substances. Reduction catalysts are the first stage in the purification process, where the catalyst break apart the chemical bonds of nitric oxides by making stronger bonds with the nitrogen than the nitrogen is bonded to the oxygen. In the oxidation catalyst, the remaining pollutants, generally carbon monoxide and hydrocarbons are burned to encourage bonding between the carbon and hydrogen atoms of the pollutants and the oxygen in the environment to produce carbon dioxide and water.

The catalytic converters are mainly equipped in the exhaust system of the automobiles, in order to remove

- Excess Hydrocarbons
- Nitrous oxides
- Carbon monoxide
- Sulphur Oxides

The catalytic converter consists mainly of the following components: 1) Diffuser 2) Monolith and 3) Reducer. These are enclosed in an assembly and attached to exhaust silencer before muffler, as shown in Figure 1.

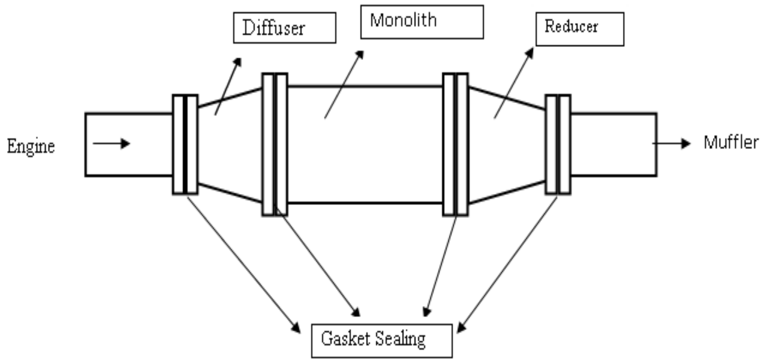


Figure 1: Typical Catalytic Converter Assembly

It can be seen that for Euro IV itself, which is implemented nationwide w.e.f 1st April 2017 as BS IV in India, stipulates 4% CO; 0.55% HC; 3.5% NOx and 0.03% PM. Compared to this Euro VI implemented in European cities stipulate 1% CO & 0.06% NOx and particularly very low HC and PM. This stipulation is posing severe restriction on NOx reduction. NOx level reduction causes increase in CO and CO level reduction causes increased NOx emission. Hence, a compromise is to be arrived at CeO_2 has been found as an efficiently suitable oxygen storage material for the wide application of TWC (Three-way Catalytic Converter) as shown in the following reactions:

$$CeO_2 \rightarrow CeO_{2-\delta} + \delta/2O_2 \quad \text{(Lean region)}$$

$$CeO_{2-\delta} + \delta/2O_2 \rightarrow CeO_2 \quad \text{(Rich region)}$$

Oxygen requirement for oxidation depends on Air/Fuel ration (Standard) and Air/Fuel ration (Stoichiometric). The engine exhaust gas composition is commonly classified in terms of λ which is ratio of $\frac{actual\ engine\ A/F}{stoichometric\ engine\ A/F}$

Thus, due to unique redox property of CeO_2 (Cerial) of storing oxygen during lean conditions and release during

rich conditions, it has been selected as catalyst.

Over the last four decades, various technologies are used for reducing emission from automobile exhaust. They are:

- Improvement in the engine design
- Air injection
- Multi point Fuel injection system instead of carburetor / fuel injectors
- Exhaust gas recirculation
- Catalytic converter
- Evaporator emission control
- Improvement in road condition and traffic network.

During recent times, as Euro norms have drastically reduced CO & NO_x levels, researches are concentrating on this aspect by trying different catalysts in catalytic converters.

In Indian scenario, as it is a developing country, it cannot afford to scrap old diesel vehicles like buses, trucks and taxis. Hence, these old vehicles need retrofit of Catalytic Converter. The developed catalytic converter by the authors of this paper is aimed as cost effective product, which can be sold at affordable price for retrofitting old vehicles.

Design of Catalytic Converter & Fabrication

Based on Tata Indica Diesel car engine specifications, the exhaust gas volume is calculated and the dimensions of the oxidation and reduction canisters are arrived.

Table 3: Specifications of Diesel Engine

Particulars	Specifications
Engine	DDiS Diesel engine
Maximum power	75 psra 4000 rpm
Speed	1500 rpm
Fuel	Diesel
No. of cylinders	Four
Maximum torque	190 Nm ra 2000 rpm
Bore diameter	69.6 mm
Stroke length	82 mm
Starting	Self starting
Working cycle	Four stroke
Method of cooling	Water cooling
Method of ignition	Compression
CC	1248

The catalytic converter assembly consists of particulate filter, canister, perforated circular housing, spacer ring, exhaust gas flow deflector and arrangement for back pressure measurement. The clay marbles coated with catalyst were arranged into a perforated canister. The inner and outer diameters of circular housing were 132 mm and 140 mm, respectively. A suitable flow deflector was arranged into the divergent portion of catalytic converter. A spacer ring was used in housing to prevent leakage of exhaust gases. Circular ring was used to reduce diameter of perforated housing.

CLAY MARBLE PREPARATION

The pot makers' Clay is taken and sufficient water is added to make the clay workable paste. The wet clay is then hand rolled into 20mm diameter marbles, as shown in Figure 2.

Figure 2: Clay Marbles

These clay marbles are then dried in open air at room temperature for one day. The excess moisture content in the clay will be evaporated and the clay marbles will become hard. These dried clay marbles are then heated in a furnace up to a temperature of 350°C, with a heating rate of 10°C per minute initially, and after reaching 100°C the rate of heating is increased to 15°C per minute. The marbles are then cooled to room temperature in the furnace itself for one day. This will make the marbles harder and now ready for the catalyst coating.

Optimization of Marble Size

The variation of void space is a cubic curve not a straight line. Most economical is 10mm as it gives minimum void space. But, the flow resistance will be high and hence back pressure of gasses increases reducing efficiency of engine and resulting in more fuel consumption.

Hence, 20mm diameter is optimum as it gives maximum surface area of and minimum resistance (can be experimentally verified by testing different marble sizes using a small canister and noting pressure drop). Hence, it is decided 20mm diameter is suitable for this experiment. Detailed calculations as to how 20 mm dia was arrived at are shown in Annexure I.

COATINGS – WASH COAT, OXIDATION CATALYST& REDUCTION CATALYST

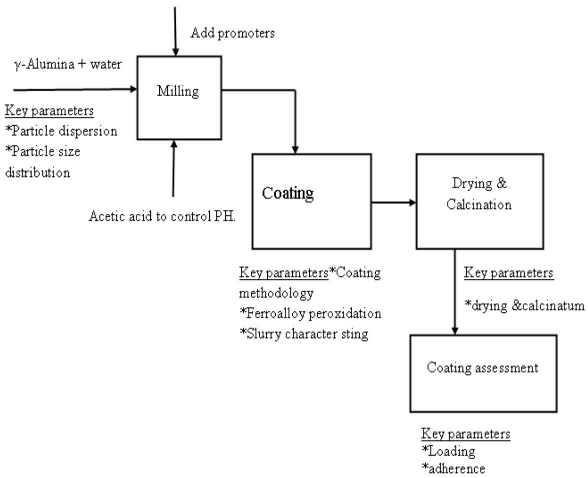


Figure 3: Preparation Path of Wash Coatings

Catalyst and Substrate Preparation in the Laboratory

Catalyst Slurry Preparation for Wash Coating

Aluminum oxide (Alumina) was used as wash coat material to increase the coating strength to surface of Clay marbles or Pellets. Twenty five grams (25gm) of alumina was added into five grams (5gm) of polyvinyl alcohol (PVA) which is a water-soluble synthetic polymer and are being used in papermaking, textiles, and a variety of other coatings. 2ml acetic acid with 50 ml of distilled water was added to get aluminum oxide slurry. The slurry was then stirred at 600rpm for one hour. The figure 4 (b) shows the prepared catalyst slurry.

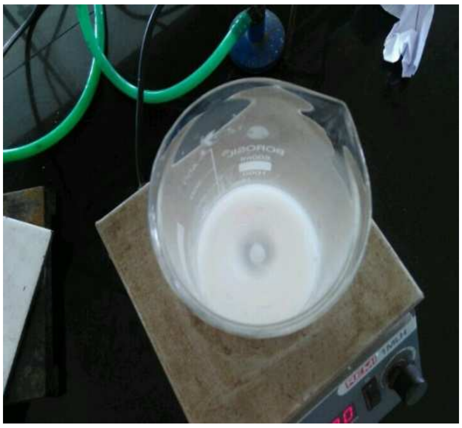
Material Selection for Substrate

Some materials like copper, stainless were used as monoliths substrate and the authors have used clay as it has good physical properties to absorb the gases. The clay is made into round marble shape to a diameter of 20mm, which gives more surface area and is coated by catalyst.

Treatment of Coating on Clay Marbles Substrate: Done in Three Steps

Wash Coat Material is Applied in Step 1 by Dip Coating

Aluminum oxide is a chemical compound of aluminum and oxygen with the chemical formulaAl_2O_3.



(a) (b)

Figure 4: a) Prepared Clay Marbles, (b) Finished Mixture of Metal Catalyst and Wash Coat Slurry

The Clay marbles substrates were then coated with the metal catalyst by dipping technique. Coated substrates are calcined. In this process, clay marbles substrate was immersed into prepared catalyst slurry for the duration of 15·20 minutes. Then, the coated clay marbles substrate was removed from catalyst slurry. They were dried in an oven at a temperature of 120°C for 2hours before being calcined in a muffle furnace. Calcination is a process in which, a material is heated to a high temperature without fusing, so that hydrates, carbonates, or other compounds are decomposed and the volatile material is expelled. Calcination is done at a temperature of 250°C in a muffle furnace for 30 min.

Figure 5: Wash Coated Clay Marbles

Catalyst Slurry Preparation for Oxidation Coating

Cerium (IV) oxide is an oxide of the rare earth metal cerium. It is a pale yellow-white powder with the chemical formula CeO_2. 10gm of Cerium (IV) oxide was added into 2.5gm of polyvinyl alcohol (PVA), which is a water-soluble synthetic polymer and 2ml acetic acid with 20 ml of distilled water to get Cerium (IV) oxide slurry. The slurry was then stirred at 600rpm for one hour. After completing the slurry preparation, wash coat coated clay marbles substrate was coated in the same way as above. Figure 7 (a) shows the complete cerium oxide coated clay marbles substrate.

(a) Cerium Oxide Coating Substrate **(b) Zirconium Dioxide Coating Substrate**

Figure 6: Catalyst Coated Clay Marbles

Catalyst Slurry Preparation for Reduction Coating

Zirconium dioxide (ZrO2) is a white crystalline oxide of zirconium. 10gm of Zirconium dioxide was added into 2.5gm of polyvinyl alcohol (PVA), which is a water-soluble synthetic polymer and 2ml acetic acid with 20 ml of distilled water to get Zirconium dioxide slurry. The slurry was then stirred at 600rpm for one hour. After completing the slurry preparation, clay marbles substrate which are already coated with wash coat are coated with the catalyst by the coating process repeated as above. Figure 7 (b) shows the complete Zirconium dioxide coated clay marbles substrate.

Preparation of Canister

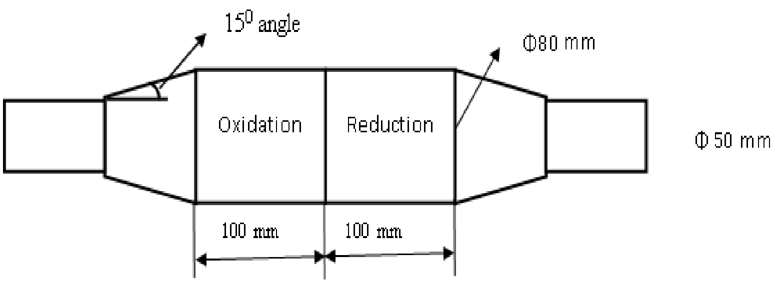
Canister is a cylindrical container used for storing clay marbles. G.I sheet is used for the preparation of canister. It is prepared with dimensions of 100mm length and 80mm diameter according to the dimensions of converter housing. The G.I sheet is cut into 250mm* 90mm, this sheet was shaped into cylinder and spot welded. Two round plates are cut. They are provided with 2mm holes so, that gas can be flow through it. These plates are welded to the cylinder to be used to hold the coated clay marbles as caps.

a) Cylindrical G.I sheet **(b) Canister cap**
Figure 7

Catalytic Converter Housing Fabrication

The catalytic converter housing used for keeping coated substrate in position consists of

- Inlet pipe
- Diffuse
- Oxidation Catalyst housing
- Reduction Catalyst housing
- Reducer
- Exhaust pipe as given in figure 8 (a)



(a)

(b) **(c)**
Figure 8: (a) Housing Section (b) Inserting Substrates into Casing (c) Complete Catalytic Converter Assembly

Using thick mild steel sheet, two cone shaped objects are fabricated to serve as diffuser & reducer. Two cylindrical shaped objects are fabricated to serve for housing canisters prepared earlier. The four components are welded with suitable flanges, and the assembled housing is shown in figure 8 (c).

TESTING OF CATALYTIC CONVERTER FOR ON ROAD DIESEL ENGINE

Experimental Setup

Figure 9 shows the on road diesel engine vehicle, which is used for the performance evaluation of Catalytic converter which is Tata Indica Diesel car.

Figure 9: Performance Evaluation without Catalytic Converter

The engine is started and using gas analyzer, the values of Co, HC are noted after engine reached steady state. Then, the assembled catalytic converter is attached to the exhaust pipe and readings are taken.

Figure 10: Performance Evaluation of Diesel Engine with Catalytic Converter

DISCUSSION OF RESULTS

The catalytic converter assembly with clay marbles on road car as shown in figure

Model B

Gas Analyzer results for clay marbles

Table 4

	CO % vol	HC ppm	$C0_2$ % vol	NO_x
Without catalytic converter	0.509	446	3.259	0.18
With catalytic converter	0.261	324	1.326	0.08
Effective reduction (%)	**48.72**	**27.35**	**59.3**	**55**

Figure 11: Result without Catalytic Converter

Figure 12: Result with Catalytic Converter

CONCLUSIONS

- Initially, geometry of substrate channels was optimized using CFD program. It is observed that between triangular, square hexagonal and circular channels are most effective, as they have maximum surface area when coated with catalyst. The CFD details are not included in preview of paper.
- The coated clay marbles offer maximum surface area of the oxidation, reduction catalysts. However, smaller marbles increase effective surface area. 20 mm marbles were used as a trial in this experimentation.
- CeO_2 and ZrO_2 help reduction of NO_x levels in the exhaust gasses, as they are useful in oxygen storage.
- The results indicate that the pollution levels are drastically reduced CO = 48.72%, HC=27.35%, CO_2= 59.3%, NO_x= 55%.

The authors are involved in carrying out the above modifications in furtherance of this research.

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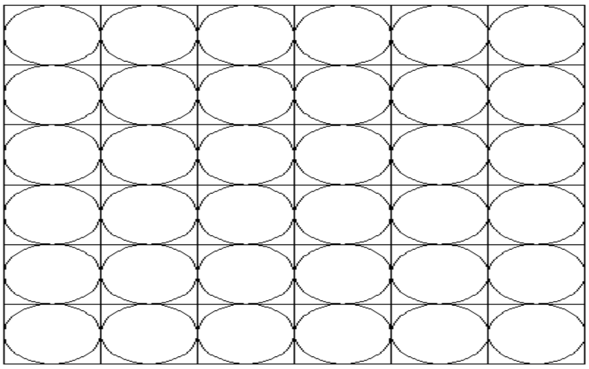
ANNEXURE - I

Calculation of Void Space in a Canister



If a = 10mm;

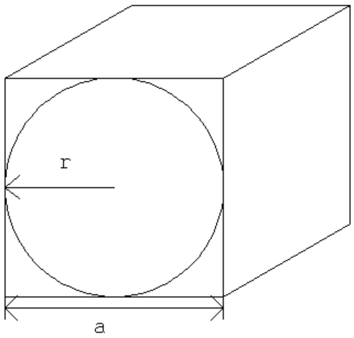
Cube volume = 1 cm^3

Sphere volume = $\frac{4}{3}\pi\left(\frac{1}{2}\right)^3$

$= \frac{4}{3}\pi\left(\frac{1}{8}\right)$ = 0.5233

Void space = 1- 0.5233

= 0.4767 cm^3



$$r = \frac{a}{2}$$

Volulme of cube = a^3

Volume of marble = $\frac{4}{3}\pi\left(\frac{a}{2}\right)^3$

If a = 2cm = 20mm

Cube volume = 8 cm^3

Marble volume = $\frac{4}{3}\pi\left(\frac{2}{2}\right)^3 = \frac{4}{3}\pi$ cm^3

= 4.187 cm^3

Void space = 8 – 4.187 = 3.813 cm^3

If a =20 mm

Then void space is less in 20mm marbles?

For 40 mm

a = 4 a^3 = 64 cm^3

r = 2 $\frac{4}{3}\pi r^3 = \frac{4}{3}\pi 8$ = 33.49 cm^3

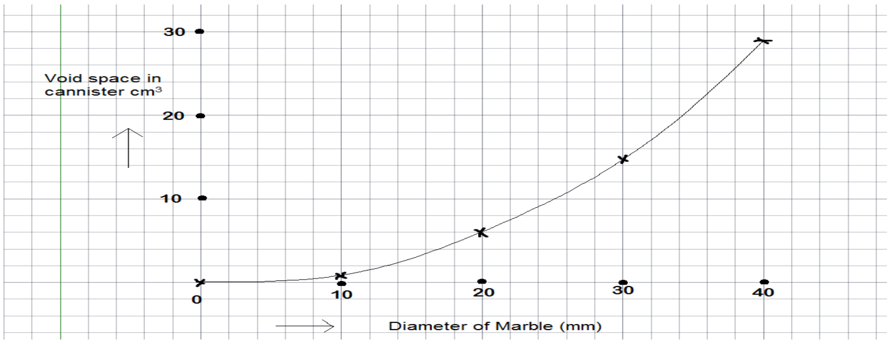
space = 64 – 33.49 = 30.51 cm^3

for 30 mm

a = 4 a^3 = 64 cm^3

r = 1.5 $\frac{4}{3}\pi(1.3)^3$ = 14.13 cm^3

space = 12.87 cm^3



Number of marbles in a canister 8cm×10cm

Volume = $\pi\left(\frac{8}{2}\right)^2 \times 14 = 703.36cm^3$

20mm marble volume $\longrightarrow$4.187cm^3

Number of marbles = $\frac{703.36}{4.187} = 168$

40mm marble volume $\rightarrow$33.49cm^3

Number of marbles = $\frac{703.36}{33.49} = 21$

10mm marble volume $\rightarrow$ 0.5233cm^3

Number of matbles = $\frac{703.36}{14.13} = 49.77$

Surface Area

$$10mm\phi \rightarrow 4\pi\left(\frac{1}{2}\right) = 6.28cm^2$$
$$20mm\phi \rightarrow 4\pi 1 = 12.56cm^2$$
$$30mm\phi \rightarrow 4\pi 1 = 18.84cm^2$$
$$40mm\phi \rightarrow 4\pi 2 = 25.12cm^2$$

In Canister

$10mm$		$1475 \times 6.28 = 9263cm^2$
$20mm$		$168 \times 12.56 = 2110cm^2$
$30mm$	Marbles	$55 \times 18.84 = 1036cm^2$
$40mm$		$23 \times 25.12 = 578cm^2$

So the surface area versus void available in canister $\rightarrow$Volume of canister = 703.36cm^3

Size of Marble	Volume of Marble(cm^3)	Number of Marbles	Number of Marbles Filled	Volume of Marbles (cm^3)	Volume of void space (cm^3)
10mm	0.5233	1344.08 (1343)	1343	702.79	0.57
20mm	4.184	167.9866 (167)	167	699.23	4.13
30mm	14.13	49.77 (48)	49	692.37	10.99
40mm	33.49	21.025 (20)	20	669.8	33.56

The void space is less for 10 mm marbles but the fabrication of that size is difficult and quantity required is also very large, the authors have chosen the 20 mm marbles which are having a void space of 4.13 cm^3 which is very less when compared to 30 mm and 40 mm size marbles.